NWL TECHNICAL REPORT TR-2470
August 1970

PARASITIC RF GAS DISCHARGES AS RECTIFIERS AND INTERFERENCE GENERATORS

Helmut A. Schwab

U.S. NAVAL WEAPONS LABORATORY
DAHLGREN, VIRGINIA

Distribution of this document is unlimited.
(CNM Control No. 1134)

43

U. S. NAVAL WEAPONS LABORATORY
Dahlgren, Virginia
22448

Steven N. Anastasion, Capt., USN
Commander

Bernard Smith
Technical Director

NWL Technical Report TR-2470
August 1970

Parasitic RF Gas Discharges As Rect·iers and Interference Generators

Helmut A. Schwab

Distribution of this document is unlimited.
(CNM Control No. 1134)

ABSTRACT

Gas discharges can be maintained in air at atmospheric pressure by rf power. In high intensity fields, for example in the vicinity of radiating antennas, enough power can be coupled into conducting structures to make parasitic discharges possible. They may be started when intermittent contact between conductors is made. It has been found that the discharges are of two distinct types, an rf glow and an rf arc type. If the discharge type alternates with the polarity, highly asymmetric voltage current characteristics result. This allows rf discharges to rectify rf currents. By their nonlinear characteristics they also produce numerous harmonics of the frequency at which they are maintained. Thus parasitic rf discharges can act as broad band interference generators.

FOREWORD

This report is a summary of the results of various research projects on radio frequency gas discharges performed at NWL. This work was funded through the Independent Research Program of the U. S. Navy.

Released by:

J. E. COLVARD
Head, Advanced Systems Department

TABLE OF CONTENTS

BLANK PAGE

I. INTRODUCTION

It is a well known fact that parasitic gas discharges on high voltage power lines can produce a considerable amount of radio frequency noise.[1,2] While these discharges convert low frequency (60 Hz) power into rf power, the opposite is also possible. Parasitic radio frequency (rf) gas discharges can rectify rf currents and produce dc and a wide spectrum of low frequencies. On the other hand, having highly nonlinear voltage-current characteristics, they can also produce very high order harmonics of the frequency at which they are maintained. This can cause severe interference problems.

One of the reasons these phenomena have not received much attention in the past is the fact that it takes considerable rf power to maintain a discharge at atmospheric pressure. A power level of at least several watts and voltages above 275 V (peak) are necessary.[3] While these levels are considerably above what electromagnetic compatibility engineers usually consider they are available in the vicinity of rf power transmitters. Aboard ship, for example, operations must often be performed at short distances from radiating antennas. It is not suprising, therefore, that difficulties involving rf discharges were first encountered aboard ship.

One example of this is the situation on the flight deck of an aircraft carrier, where aircraft and ordnance must be handled, while communications and radar antennas provide a high field intensity at many frequencies. Many of the ordnance items are electrically initiated. Under certain conditions it is possible that an rf current is induced into the firing circuits which is of sufficient amplitude to cause unintentional initiation of explosive trains or ignition of a rocket motor. A seemingly obvious solution to this problem is to put low pass filters into the firing circuits which stop rf currents but pass low frequency firing signals. When the weapon umbilical cable is connected to the aircraft, however, rf discharges may occur between contacts. These discharges can rectify and produce low frequency signals which will pass the filter, thus making it ineffective. The investigation reported here was originally triggered by this problem.

There have been a number of publications recently on nonlinear effects occuring in the vicinity of radiating antennas.[4,5] Significantly, they also deal with problems encountered aboard ship. While no specific reference to rf gas discharges is made in these papers, it seems that in at least one case (Ref. 4) rf discharges must be assumed for a satisfactory explanation of the reported observations. This example will be discussed in section V.

In this paper, we will first discuss those types of rf discharges that are encountered in practice and the parameter ranges involved. Next, we will explain the mechanisms involved in rectification and finally turn to the generation of harmonics.

II. TYPES OF RF DISCHARGES AT ATMOSPHERIC PRESSURE

1. General

The first step in this investigation was to construct equipment by which rf discharges could be maintained under controlled conditions and their voltage current characteristics studied The essential components of the apparatus used are shown in Figure 1. A radio frequency power transmitter (URT-3) provided up to 500W of rf power. It was connected to the discharge gap G via an impedance matching network and a current limiting resistor R_s. Discharge voltage and current waveforms were displayed on an oscilloscope screen. The wideband capacitive voltage divider was used for symmetrical waveforms, while the compensated resistive divider was used for waveforms containing a dc component, which will be discussed later. The electrode geometry is shown in Figure 2. The electrodes were cooled by circulating water. Details on the construction of the apparatus and its frequency behavior are given in Ref. 3.

Voltage current characteristics of rf discharges were studied for a large variety of parameters. A current range of 50 mA to 2A and a frequency range of 0.3 to 30 MHz were covered. Electrode distance ranged from 0.025 to 2.5 mm. The value of R_s was varied between 100Ω and 10 KΩ. All discharges were maintained in air or atmospheric pressure.

The essential finding of these studies was that in practice we encounter only two types of rf discharges, each being closely related in its characteristics to the corresponding dc discharge. One type is the glow discharge, the other one the arc discharge. In the laboratory, under extreme conditions it seems possible to maintain a third type, the so-called abnormal glow discharge, for short periods of time. Under ordinary field conditions, however, this last type will not occur. We will now turn to a description of the characteristics of these three discharge types.

2. RF Glow Discharges

To obtain a stable glow discharge we must use metal electrodes with a clean, smooth surface. For starting the discharge we move the electrodes together until they make contact and then pull them apart to the desired distance. Typical waveforms of voltage across the discharge and current through it are shown in

Figure 3 for a frequency of 1 MHz. Referring to this figure we can characterize essential discharge behavior as follows: The voltage across the discharge rises about linearly with time until it reaches a value V_i sufficiently high for ignition, which is about 350 V. At the ignition point, the voltage usually drops a little, while a rapid increase of discharge current begins. The final value of the discharge current depends on R_s and the power delivered by the rf generator. During current flow, the discharge voltage stays high at around 300 V or more. When the voltage drops below the minimum necessary to maintain the discharge, the current quickly decreases towards zero. We define I_m as the maximum value of discharge current in one half cycle and V_m as the discharge voltage at the time I_m is obtained. In Figure 3, for example, we have I_m = 0.6 A and V_m = 340 V.

This is only a schematic description of discharge behavior, but it is adequate for the purposes of this report. More details have been published elsewhere. For example, before the voltage reaches V_i, the current is not zero. There is a preignition current I_c which grows with frequency and is about 3% of I_m at 1 MHz, as Figure 3 shows. This preignition current is analyzed in reference 6. Also, the reignition voltage V_i deviates from 350 V at frequencies below 1 MHz and for certain small electrode distances. This phenomenon is discussed in reference 7.

The experiments reveal the following properties of rf glow discharges:

a. The discharge shows a light intensity and color distribution analogous to a dc glow discharge in air at atmospheric pressure. The difference is that the blue cathode glow is attached to both electrodes, since the discharge polarity alternates.

b. The electrode area A_o covered by the blue glow increases in direct proportion to I_m so that the current density $J_m = I_m/A_o$ is a constant.

c. The discharge voltage V_m is almost independent of current (see Figure 4).

d. In the frequency range investigated so far, V_m has been found to be essentially independent of frequency

e. V_m, increases only slowly with an increase of electrode distance d (Figure 4).

f. Even with very small electrode distances ($d \approx 2 \times 10^{-3}$ cm) there is a minimum voltage of 275 V necessary to maintain the discharge.

These features are clearly the same as those of dc normal glow discharges which have been studied extensively.[8-10] It seems then that the principal discharge mechanism, which is characteristic for a dc glow discharge, is also at work in these rf discharges. What is this mechanism? And is it reasonable to expect that a discharge can be established in a time so short that we can account for the continuous change of direction even at 30 MHz?

The characteristic feature of a glow discharge is the mechanism of electron emission at the cathode. In a glow discharge, electron emission is caused by secondary emission through ion bombardment and by photoelectric emission through radiation from the discharge gas (Ref. 10). For this mechanism to work, the cathode can be cold. To release a sufficient number of electrons from the cathode, however, it takes considerable ion velocity. The ions gain this velocity by crossing the "cathode fall", a region of space charge concentration and resulting high electric field strength in front of the cathode. The total voltage across the cathode fall of a glow discharge must be on the order of several hundred volts in general and about 275 V in our particular case. It is this electron emission mechanism that is characteristic of a glow discharge and that determines the minimum voltage of 275 V to maintain it. With respect to the time required to establish a discharge it has been shown by Fletcher[11] that breakdown can take place in times of less than 1 nsec, provided enough electric field strength is available in the gas. From the voltage-current waveforms we learn that it takes about one third of each halfcycle to establish the discharge, which is 5 ns at 30 MHz. Therefore we can easily account for the speed with which the discharge changes direction even at such high frequencies.

More details of glow discharges, both dc and rf, are described in the literature.[8-10,12] We need not discuss them here since they are not essential for the purpose of this report.

3. RF Arc Discharges

Just as the mechanism of electron emission from the cathode is characteristic of a glow, so it is for an arc. In an arc the electrons are emitted by thermionic emission or a combination of thermionic and field emission.[13] The surface temperature of an arc cathode must therefore be high. The velocity of the ions hitting the arc cathode does not have to be as high as in a glow, since they need not release any secondary electrons. Consequently, the cathode fall voltage of an arc is much lower than that of a glow, the order of magnitude being 30 V for the amount of current and the electrode distances considered here. This is illustrated by the waveforms of arc voltage and current shown in Figure 5, which are typical of rf arcs. Again, as we had found for glows, the voltage rises at the beginning of each halfcycle until it reaches a value V_i sufficient for ignition. V_i is about the same as for glows. When the arc current is established, however, the voltage drops to about 70 V for this electrode distance and stays low for the rest of the halfcycle. The maximum current I_m is determined by R_i and the power delivered by the rf source.

Again, the characteristics of rf arcs are much the same as those of dc arcs The discharge appears much brighter than a glow, with a particularly high light intensity near the electrodes. The current density is considerably higher than in a glow, but cannot easily be measured because of the constant movement of the position of the arc on the electrode surface. V_m (again defined at the time when I_m is obtained) as a function of current and electrode distance is shown in Figure 6.

The conditions which favor the establishment of an rf arc discharge can be understood from the necessity of having a high cathode surface temperature and a high current density. Thus, we observed the most stable rf arcs when using carbon electrodes. This can be explained by the low thermal conductivity of C. With metal electrodes a glow discharge will usually be obtained. A temporary conversion to an arc discharge is favored by the following factors: rough cathode surface, loose chips of material left on the cathode surface from filing, oxidation, salt deposits, insulating material close to the cathode which can burn or vaporize. Such influences will almost certainly cause an rf discharge to flicker between glow and arc modes. Stability of a pure rf arc discharge over longer periods of time (minutes), however, is difficult to establish, which makes measurements on rf arcs much more cumbersome than those on glow discharges. Therefore, measurements were made at 1 and 2 MHz only in this investigation. (There is no reason to assume, however, that arcs change more with frequency than glows, which were found independent of frequency in their essential features in the investigated range 0.3 - 30 MHz).

4. RF Abnormal Glow Discharges

A dc glow discharge can be converted into an arc by increasing the current to a sufficiently high value. At low pressures, the transition is gradual and the discharge traverses the region of "abnormal glow discharge" between a "normal glow" and the final arc.

In section 2 it was pointed out that the current density (at the cathode) in a normal glow discharge is constant. Increasing the current will cause the discharge to cover a larger electrode area. The transition from a normal to an abnormal glow occurs when the total cathode area is covered by the discharge. A further increase of current must then result in an increase of current density. This is accompanied by an increase in voltage across the discharge. The increase of current density and voltage are characteristic for the abnormal glow, which is also called constricted glow.

To answer the question whether this kind of discharge can be maintained at rf under our conditions, we must limit the cathode area. This was done by an arrangement shown in Figure 7. This electrode arrangement is asymmetrical so that the exposed area of one electrode is limited to the end face of a cylinder which is surrounded by insulating material. In the halfcycle in which the electrode with the limited area is cathode we should then get an abnormal glow. In the experiment it turned out that for most insulating materials the discharge immediately turns into an arc when the point of transition to an abnormal glow is reached. Since the current density even in a normal glow is high at atmospheric pressure ($I_m/A_o \approx 30 A/cm^2$), the power concentration is high in the discharge, particularly at the cathode. Under these conditions most insulating materials will be decomposed chemically and the resulting changes at the cathode surface will turn the discharge into an arc before an observation can be made. Under the microscope, burning and erosion of the insulation can be observed.

The only insulation with which an apparent abnormal glow could be established for a very short period of time (1-2 seconds) was boron nitride (BN), a highly refractory material. An example of a waveform obtained with BN as an insulator is shown in Figure 8. This photograph was exposed twice, once to record the waveforms and a second time to establish a zero voltage reference line. The current density for this example of an abnormal glow is about 3 times as high as for a normal glow and the increase of voltage above normal if about 35%. The duration of such a discharge is just long enough for taking a photograph of the waveforms, before it converts into an arc.

There is some uncertainty about whether this discharge really was an abnormal glow. We will show later (Figure 14) that a normal glow produces similar waveforms with the same electrode pair but with the insulation removed. However, the values of V_m are significantly different for the two cases. In Figure 8, V_m in the positive halfcycle is 410V, while according to Figure 14 it drops to 370V when the insulation is removed, although the electrode distance in the second case is greater. Furthermore, inspection of the insulated electrode under the microscope showed the insulation intact even after the photo of Figure 8 had been taken. So it would be difficult to argue that the discharge had more area to cover than the front end of the rod electrode. The value of V_m = 410V indicated in Figure 8 would also be hard to account for except by assuming an abnormal glow discharge. In any case, since it is so difficult to produce an abnormal rf glow discharge (at atmospheric pressure) we may conclude that in the field we will meet only two types of rf discharge: rf glows and rf arcs. For our purposes these differ mainly by the voltage necessary to maintain them. For small electrode distances this is about 300V for glows and about 30-50V for arcs. Which type occurs in a particular case depends mainly on the surface condition of the electrodes, but also on circuit parameters and the current amplitude. The electrode surface conditions are not necessarily the same for both electrodes. In this case an asymmetrical discharge may develop. This is the subject of the following section.

III. RECTIFICATION MECHANISMS

1. General

Let us now assume that enough voltage and power is available to maintain an rf discharge and consider the conditions under which rectification can take place. The necessary condition for rectification is an asymmetric voltage-current characteristic. Such asymmetry could be established in various ways. In the previous section it has been pointed out that it largely depends on electrode surface conditions whether an arc or a glow will be obtained. If the two electrodes are different, it is possible to have glow and arc discharge mechanisms alternate with polarity. This will result in gross asymmetry, but asymmetry is not restricted to this combination. It can occur even when the discharge in both halfcycles is of the same type. We will now discuss the various types of asymmetry and their behavior with respect to rectification.

2. Discharge Type Changes with Polarity

Every discharge is associated with an electric circuit, for example the circuit that supplies the power to maintain it. We will assume that all elements of this circuitry except the discharge itself are linear. In this case it will depend entirely on the electrodes, their surface conditions, geometry and material, whether we can have asymmetrical discharge behavior or not. The details of rectification, however, and the voltage-current waveforms obtained in a particular case, depend much on the electric circuitry involved. We will now discuss two simplified but typical cases.

The characteristic of the first example is a zero dc component $\bar{I}$ of the discharge current. This condition is accomplished by a capacitor C in series with the discharge as shown in Figure 9. We will assume C to be large enough so that the rf voltage across it is negligible. Also C shall have no losses. Our circuit then consists of an rf source with internal resistance R_i which delivers power to a discharge gap through a current limiting resistor R_s. The discharge asymmetry is assumed such that electrode 1 acts as an arc cathode, electrode 2 as a glow cathode.

Under these conditions we will obtain waveforms as shown in Figure 10. While the positive halfcycle shows typical arc behavior, with an arc voltage of about 40 V, the negative halfcycle is a clear glow with $V_m \approx 320$ V. We shall call this kind of discharge a glow-arc combination. Positive and negative total current are equal in each cycle. The voltage waveform, however, has a dc component $\bar{v}_c$, which in this case is about -110 V. This voltage $\bar{v}_c$, of course, is applied across the capacitor C. The instantaneous values of voltage v across the discharge, current i through it and voltage $\bar{v}_c$ across the capacitor are related to the sinusoidal source voltage through the following relation:

$$v + \bar{v}_c + i\,(R_i + R_s) = V_0 \sin \omega t; \qquad (1/\omega C \ll R_i + R_s) \tag{1}$$

This relation can be essentially verified with the waveforms shown in Figure 10 and $R_s = 500\Omega$, $R_i \approx 50\Omega$. Small discrepancies are due to R_i not being purely resistive and equal to 50Ω. We can now ask what is the maximum dc voltage $\bar{v}_{max}$ that could develop across the discharge under the described conditions. The mean voltage across the discharge is defined by

$$\bar{v} = \frac{1}{\tau}\left(\int_p v\,dt - \int_n v\,dt\right), \; \tau = 1/f; \tag{2}$$

where p indicates an integration over the positive, n over the negative halfcycle. $\bar{v}_{max}$ will be obtained if we maximize the positive and minimize the negative integral. This can be done by choosing a large value of R_s, which changes the voltage waveform of Figure 10 towards the limiting case shown in Figure 11. For small electrode distances the voltage in the arc halfcycle will rise to the ignition peak for a very short time and then stay constant as long as the arc current lasts. As $R_s \to \infty$ this approaches the full halfcycle. A similar consideration pertains to the glow halfcycle. We know from section II that for small d the glow voltage is not more than about 300V, while the arc voltage is at least 30V. Since the durations of negative and positive halfcycle are equal (R_s is large), we have

$$\left|\bar{v}_{max}\right| = 1/2 \times 300 - 1/2 \times 30 = 135\text{V}; \tag{3}$$

This limit was derived for small electrode distances, but it will not vary much with increasing electrode distance for the following reason. An increase in d will result in a increase of discharge voltage. This increase, however, cannot be much different for the two halfcycles, since it is essentially the voltage drop along the positive column part of the discharge, which does not depend on polarity. The net contribution to $\bar{v}$ as defined by equation (2) would then be zero and we would obtain the same $\bar{v}_{max}$ as before. The circuit of Figure 9 does not allow a direct current through the discharge, but a dc voltage of up to 135V can develop across it. This voltage would drive a dc current through any resistance which we would connect in parallel to the gap. For reasons of continuity this current would obviously have to return through the discharge.

If we lower this dc resistance to zero, we arrive at our second example, which is characterized by zero dc voltage across the discharge. The circuit shown in Figure 12 will ensure this condition if we assume that L has no losses. We will further assume that ωL is large enough that the rf current through it is negligible. The voltage waveform is now subject to the condition

$$\int_p v dt = \int_n v dt; \qquad (4)$$

Obviously a symmetrical voltage waveform (glow-glow or arc-arc) fulfills this condition. An asymmetrical waveform can fulfill it too, as the oscillogram of Figure 13 shows. Again, in one halfcycle we have an arc. In the other halfcycle, the ignition voltage is not even reached and therefore we have no discharge at all. Consequently, the discharge current is zero in the positive halfcycle. Except for the reignition peak the discharge in this circuit acts pretty much like an ideal diode, having a very low forward resistance of $\approx 25\Omega$ and a very high reverse resistance. The result is half wave rectification of the rf current.

Condition (4) does not forbid a glow-arc combination. We could have an arc in one halfcycle and a glow in the other provided the arc halfcycle would last considerably longer than the glow so that (4) could be fulfilled. This, however, was not investigated experimentally.

We have discussed two limiting cases as examples. In practice we will find more complicated circuits, for which both $\bar{v}$ and $\bar{i}$ will in general be different from zero.

3. Discharge Type is Independent of Polarity

We will focus our attention on glow discharges in this section, but analogous arguments apply to arc discharges. Glow-glow combinations can be asymmetrical. The basis for this is that the voltage across a discharge depends on factors like electrode material and electrode shape. Although the electrode material does not have as much influence at atmospheric pressure as at low pressures, differences can be measured.[3,8] Total variation between four materials (Au, Cu, Fe, Ni) was measured to be 10%, while it is more than 60% for these same materials at lower pressures.[14] Discharge voltage depends on electrode shape too.[3] Variations of voltage with shape are also of the order of 10%. An example is shown in Figure 14, which shows waveforms obtained with an electrode pair as displayed in Figure 7, but with the insulating material removed. The thin electrode was grounded so that it acted as cathode in the positive halfcycle. DC current through the discharge was zero. From the voltage trace we read that $V_{T} \approx 370V$ for the positive halfcycle. Again, as we described in the previous section, much of the details of rectification will depend on the particular circuit involved. We can make some general statements, however, about this type of asymmetry. First, rectification can take place with very clean, smoothly finished and well cooled metal electrodes. Second, this type of rectification produces a constant and predictable polarity dc output. And finally, since it is unlikely that practical discharge gaps have perfect symmetry, some rectification will always take place, however small the amount may be.

In summary we can say that rf gas discharges can and usually will exhibit asymmetrical behavior. This can range from weak to very strong asymmetry, depending on electrode shape, material, surface condition, etc. Rectification depends on the electrical circuits involved, but can be very efficient under favorable conditions

IV. LOW FREQUENCY GENERATION

By their capability to rectify, rf discharges can obviously generate low frequencies by demodulation, if the rf oscillation maintaining the discharge is amplitude modulated. They also can produce the difference frequency of two oscillations by mixing. In this section, however, we will turn our attention to a different mechanism, by which rf discharges can convert a single frequency, unmodulated rf oscillation into a wide spectrum of low frequencies.

This mechanism is based on random changes in the discharge. Electrode conditions, especially when arcs are involved, are not stable over long periods of time. Arcs can turn into glows and vice versa, spontaneously. Under these conditions, the polarity of the rectified current will also change randomly or rectification may stop altogether for short periods of time. This random change of output is characteristic of glow-arc combinations. It was investigated in a circuit as shown in Figure 15. A 2 MHz discharge was used with an inductor parallel to the discharge to ensure $\bar{v} = 0$. The RC network following the diodes has a time constant of about 4 μs, so the rectified signals I_{p+} and I_{p-} will be proportional to I_m of the respective halfcycles. A typical output from the discharge is shown in Figure 16. In this photo, 1 is the reference line for I_{p-}, 2 for I_{p+}. I_{p-} is deflected in the negative, I_{p+} in the positive direction. The amplitude scale is relative and the time scale is 1 ms/div. Figure 16 shows the characteristics of the discharge output very well: the rectified current switches polarity, but its amplitude does not change. We understand this when we consider that the change in polarity is caused by a glow-arc combination turning into an arc-glow combination. This exchange of electrode function can only cause the polarity to switch, since neither the rf amplitude nor the circuitry have been altered. The case that the discharge turns into a glow-glow combination, which would result in zero rectified current (or a rather small current for a slightly asymmetric glow-glow), does not occur in the waveforms of Figure 16.

The two other traces in this figure show the peak values V_{p+} and V_{p-} of discharge voltage. These quantities were obtained by a circuit similar to the one used for I_{p+} and I_{p-}. The reference line for V_{p+} is 2 and it is deflected positively. The reference line of V_{p-} is 3 and it deflects in the negative direction.

V_{p+} is high when I_{p+} is high and low when I_{p+} is zero. The reason for this relation becomes clear when we refer to Figure 13 and read 350V for the peak voltage in the arc halfcycle, while the peak voltage in the other halfcycle reaches only 250V.

The waveforms in Figure 16 show that polarity changes can take place very quickly. As read from the oscillogram, the rise time is not more than about 100 μs, so that we will have significant spectral components of this waveform up to at least 10 KHz.

V. HARMONIC GENERATION

We will restrict the discussion in this section to glow discharges. Typical waveforms of glow discharge current and voltage are shown in Figure 3. It is obvious from these oscillograms that both waveforms contain many harmonics. Both waveforms depend, however, on the circuit associated with the discharge and so does the degree of distortion. This will become apparent immediately when we consider the two limiting cases of $R_s \to 0$ and $R_s \to \infty$. In the first case we essentially force a sinusoidal voltage across the discharge. In an experiment the peak value of the voltage must be adjusted to slightly above the reignition voltage, so that reignition becomes possible and simultaneously the discharge current does not become excessively large. Under these conditions we can have discharge current only during the short period where $v > V_{min}$. The resulting waveform is approached by the curves shown in Figure 17a, which was obtained with $R_s = 100\Omega$. The other extreme is $R_s \to \infty$, which is equivalent to forcing a sinusoidal current through the discharge. The discharge voltage then will reach V_i as soon as the current begins and hold the value of V_m for the period of sustained current flow which is the full halfcycle. Waveforms approaching this condition are shown in Figure 17b, taken with $R_s = 2000\Omega$. The spectra of the two current waveforms of Figure 17 are shown in Figure 18, normalized to the amplitude of the fundamental.

If a transmitter induces such discharge currents in metallic structures around it, energy can be re-radiated at harmonic frequencies. By this mechanism, discharges can contribute significantly to radio noise present in the vicinity of power transmitters. Measurements of radio noise which was apparently caused by this mechanism were reported in a recent paper.[4] The authors report an increase of noise level in the telemetry receivers of an Apollo spacecraft tracking ship, when the HF transmitters were operated. The source of this interference was found in the safety barrier chains around the weather decks. The authors argue that "the motion of the chains created, in effect, a small switch at each link-to-link connection • • • Where the chains were illuminated with rf each link became an interference generator • • •" Harmonics of the impinged rf as high as S-band where detected. Tightening of the chains to prevent intermittent contact cured the problem. If we assume that a simple opening and closing of contacts between chain links was involved, we have to conclude that the rf current in the chain must essentially be of the frequency radiated by the transmitter, but amplitude modulated by the action of these switches. Since these chain links have considerable inertia, we could not assume a very high switching speed. The rf current in the chain would be limited to a frequency band around the transmitter frequency. It is hard to see then, how all the high order harmonics should be created, which were observed and were obviously due to the chain motion since tightening of the chain removed them. If we assume, however, that discharges occured between the chain links, then the chain current could have contained a large amount of harmonics which would account for the measured results. Since the HF transmitters had a 10 kW (PEP) capability it is quite possible that high enough voltages were available between the chain links to maintain discharges. In any case there is no doubt that discharges are capable of causing the observed interference. Therefore, the vicinity of antennas radiating at high power levels should always be kept clear of structures that would favor rf discharges. Chains are but one example of this kind.

VI. SUMMARY

Gas discharges between a pair of electrodes in air of atmospheric pressure can be maintained by rf power. A minimum power of about 5W and a minimum peak voltage of 275V are required. In close vicinity of radiating antennas these quantities can be available between conducting structures.

The frequency range from 0.3 - 30 MHz was investigated. In this range the discharges were found to be either of the normal glow or the arc type, both of which are closely related in their characteristics to the corresponding dc gas discharges. Abnormal glow discharges can also be obtained at rf, but only under special conditions in the laboratory. The voltage necessary to maintain a glow is about 300V, the voltage of an arc about [illegible]0V. These voltages increase with electrode distance. Arcs are favored by rough electrode surfaces, sharp edges, oxidation and contamination, glows by smooth, clean metal electrode surfaces. Discharges can have asymmetric voltage current characteristics. Gross asymmetry is the result of changes of discharge type in alternate halfcycles, for example glow-arc changes. Glow-glow discharges, however, can also be weakly asymmetric, because the discharge voltage depends slightly on electrode material and shape. The details of rectification depend on the particular circuit in which the discharge is maintained. Under favorable conditions it can be very efficient and halfwave rectification can take place with one halfwave of the rf current being suppressed completely. Random changes in electrode surface properties can cause the discharge to rapidly change the polarity of its rectifying action and produce a wide spectrum of low frequencies. It can also produce low frequencies by demodulating an amplitude modulated rf oscillation.

Besides converting rf power into dc and low frequency power, discharges produce harmonics of the frequency at which they are maintained up to very high order. By their mixer and rectifier properties discharges can act as broadband interference generators. Two of the problems caused by discharges were discussed as examples.

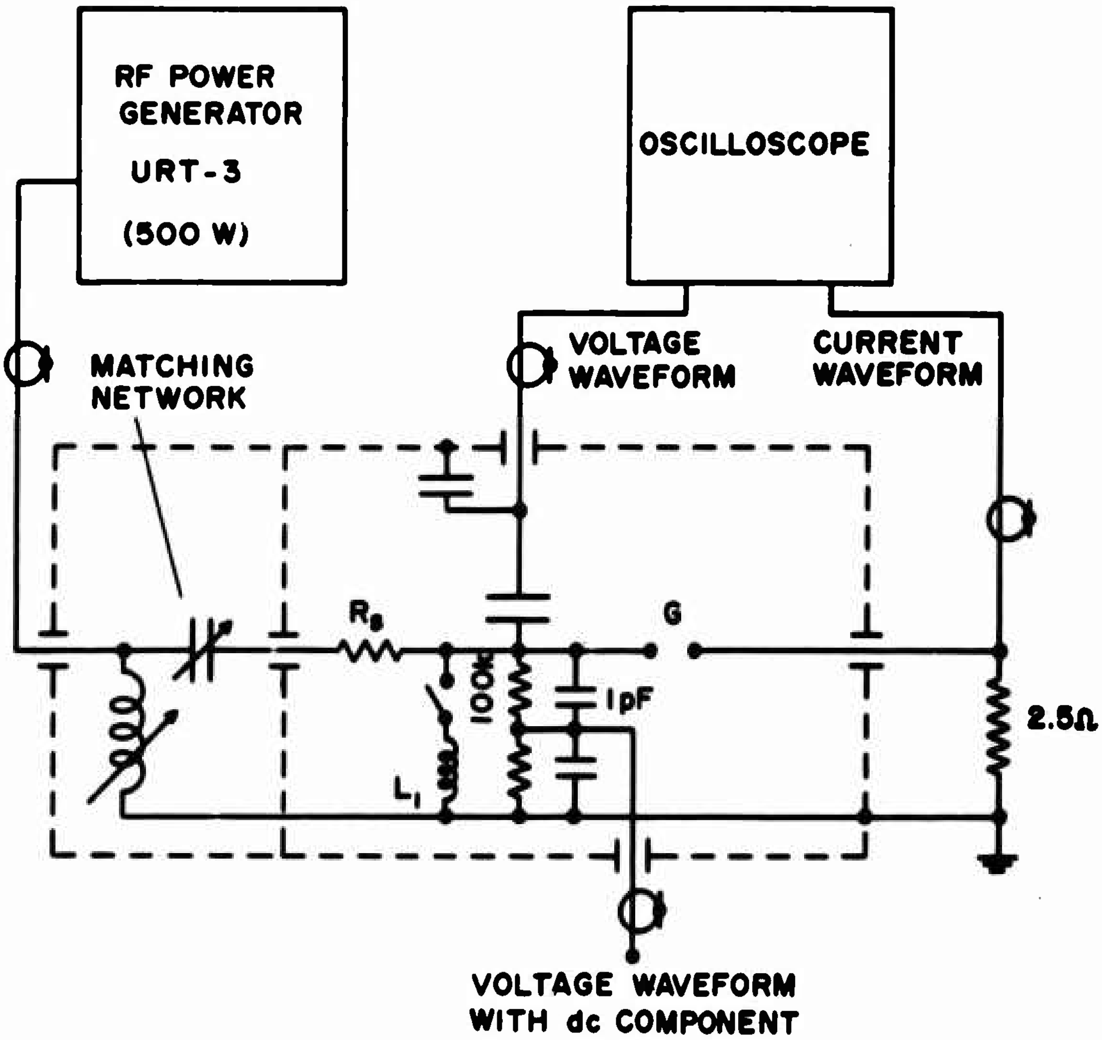


Figure 1

Apparatus used to measure discharge behavior

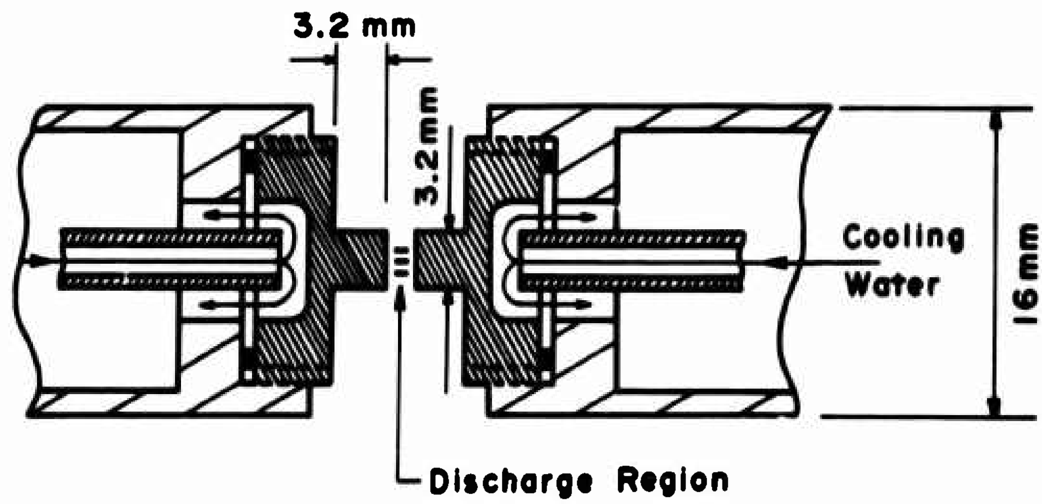


Figure 2

Electrode geometry

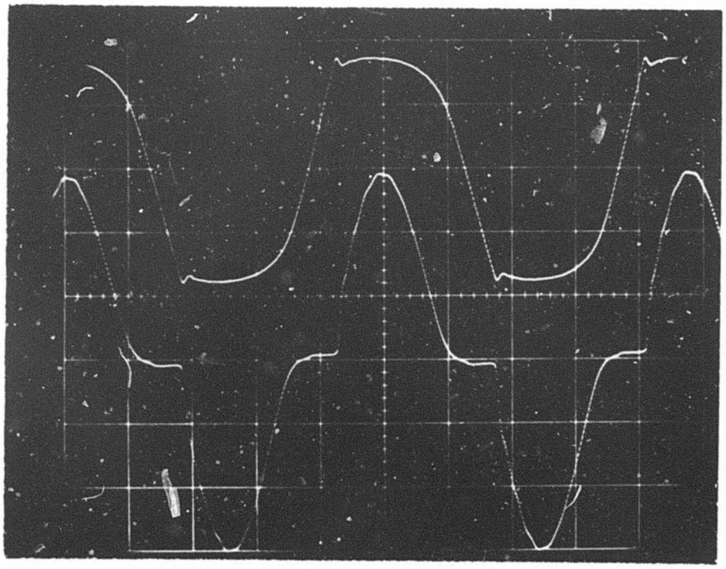


Figure 3

Voltage across a glow discharge and discharge current. Discharge between plane parallel Cu electrodes. Rs = 500Ω; d = 0.25 mm; f = 1 MHz.
Upper trace: voltage, 200 V/div.; lower trace: current, 0.2 A/div.

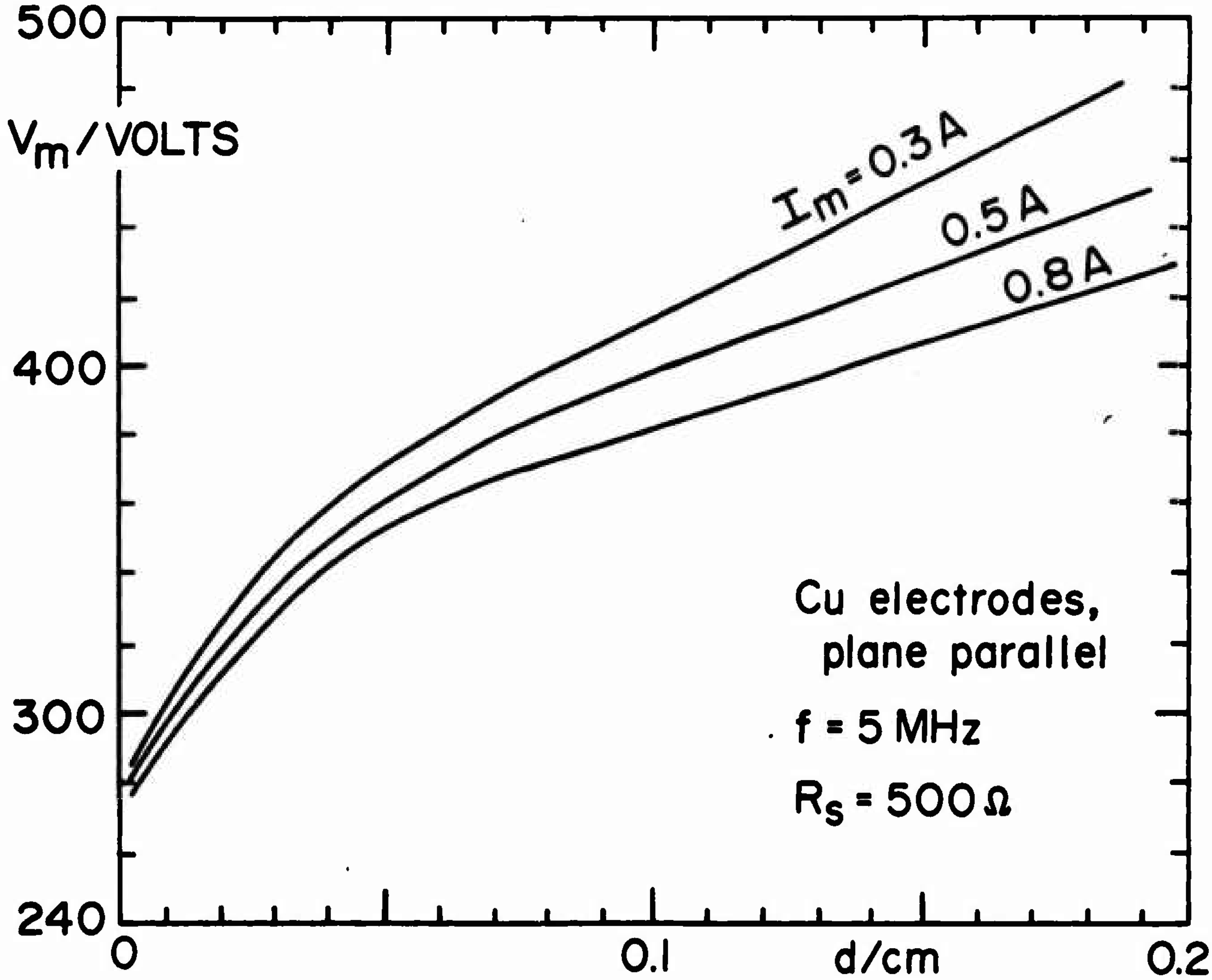


Figure 4

V_m as a function of electrode distance d for glow discharges.

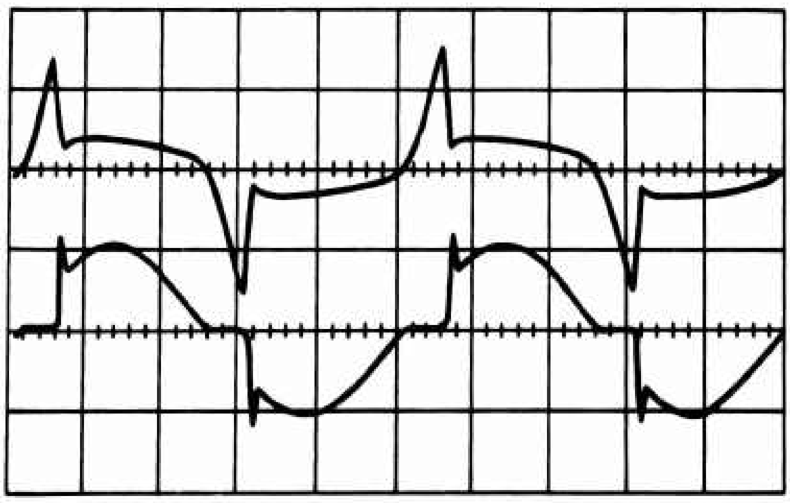


Figure 5

Voltage across an arc discharge and discharge current. Discharge between plane parallel carbon electrodes. $R_s = 500\Omega$; d = 0.7 mm; f = 1 MHz.
Upper trace: voltage, 200 V/div., Lower trace: current, 1 A/div.

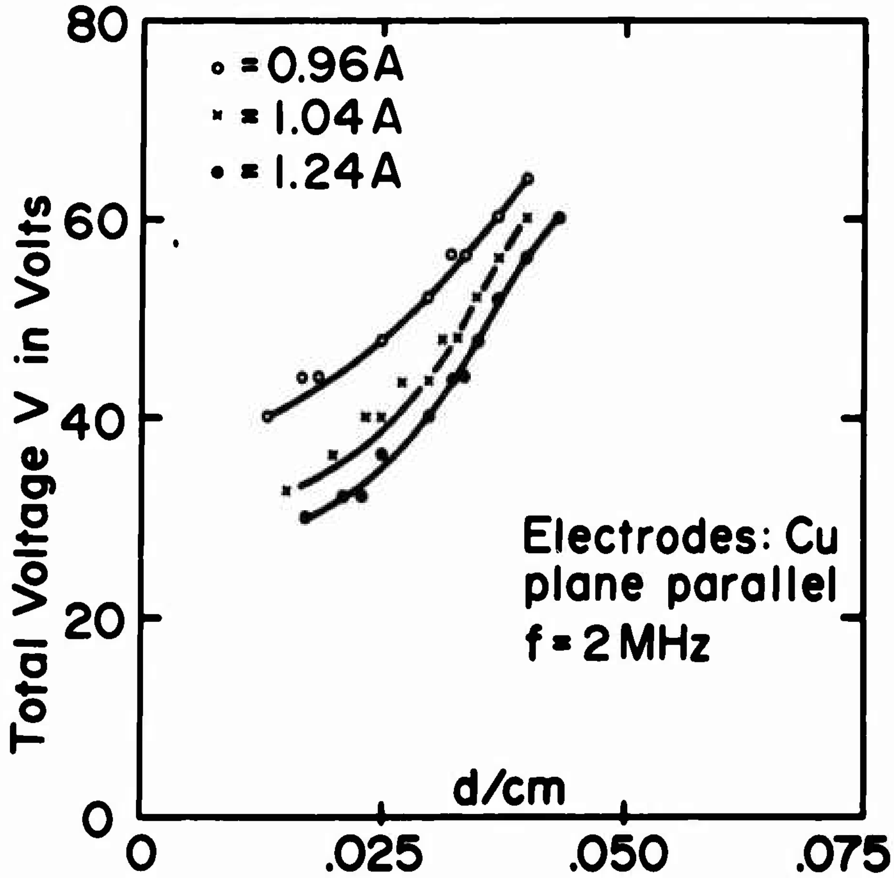


Figure 6

V_m as a function of electrode distance d for arc discharges.

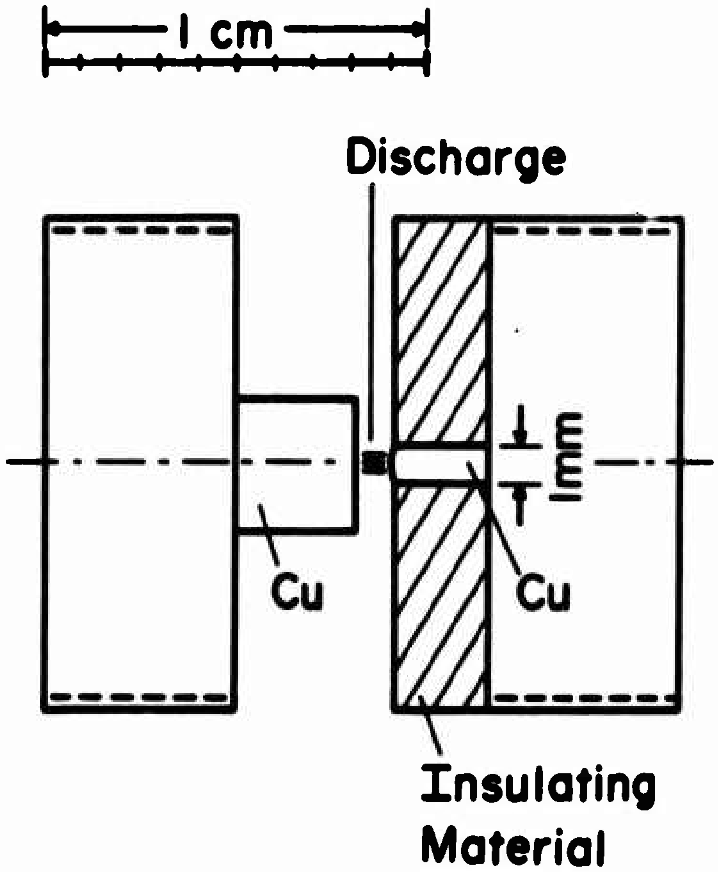


Figure 7

Electrodes used to produce an abnormal glow discharge.

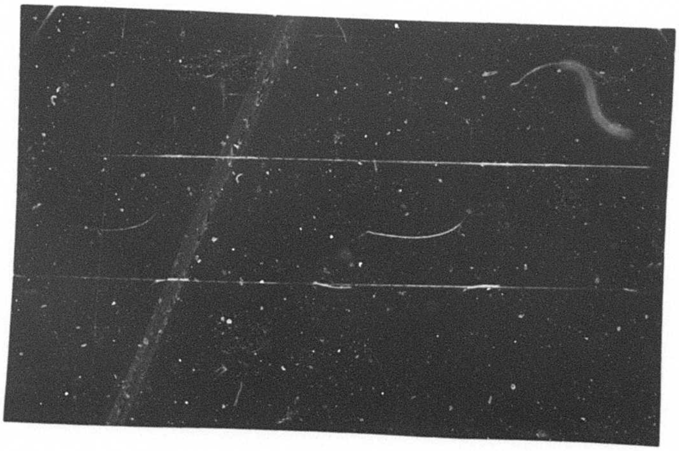


Figure 8

Abnormal glow discharge in the positive halfcycle and normal glow in the negative halfcycle. R_s = 500Ω; d = 0.025 mm; f = 1 MHz. Cu electrodes.
Upper trace: voltage, 250 V/div; lower trace: current, 0.4 A/div.

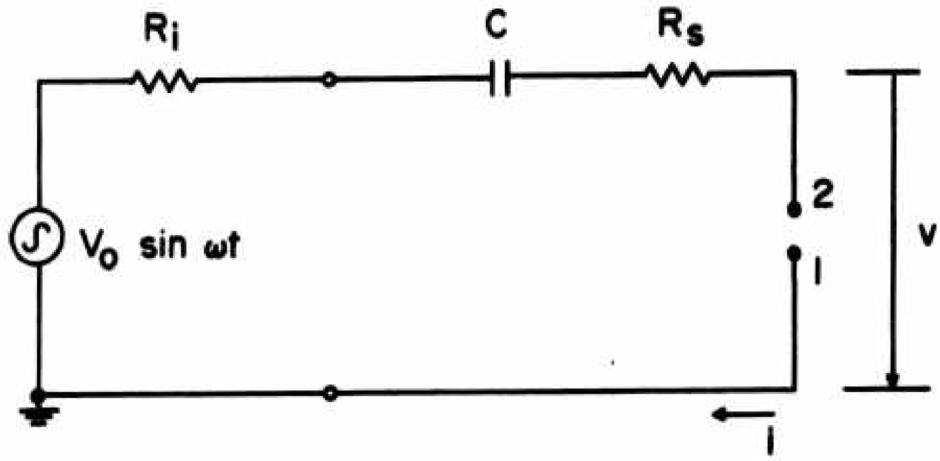


Figure 9

Circuit for discharges with zero dc component of discharge current.

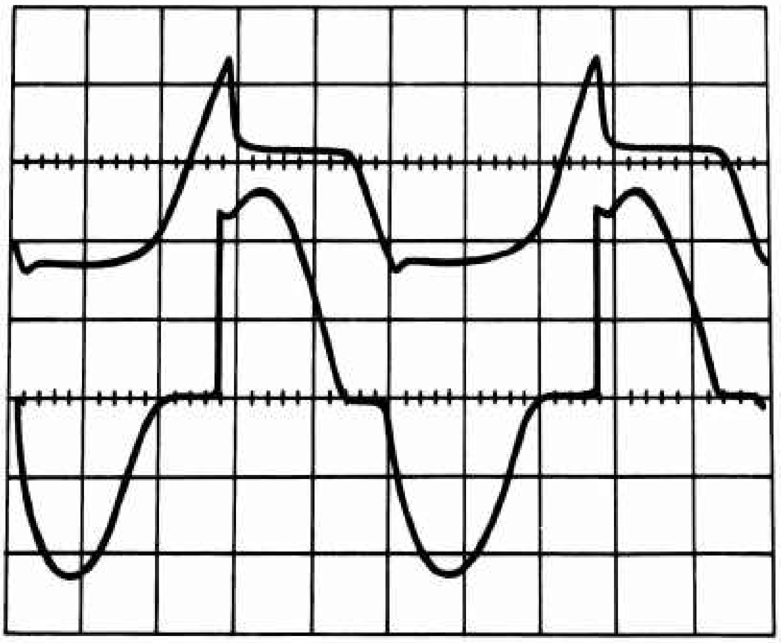


Figure 10

Voltage and current waveforms of asymmetrical discharge obtained with circuit of Figure 9. $R_s = 500\Omega$; d = 0.05 mm; f = 1 MHz. Upper trace: voltage, 250 V/div; lower trace: current, 0.4 A/div.

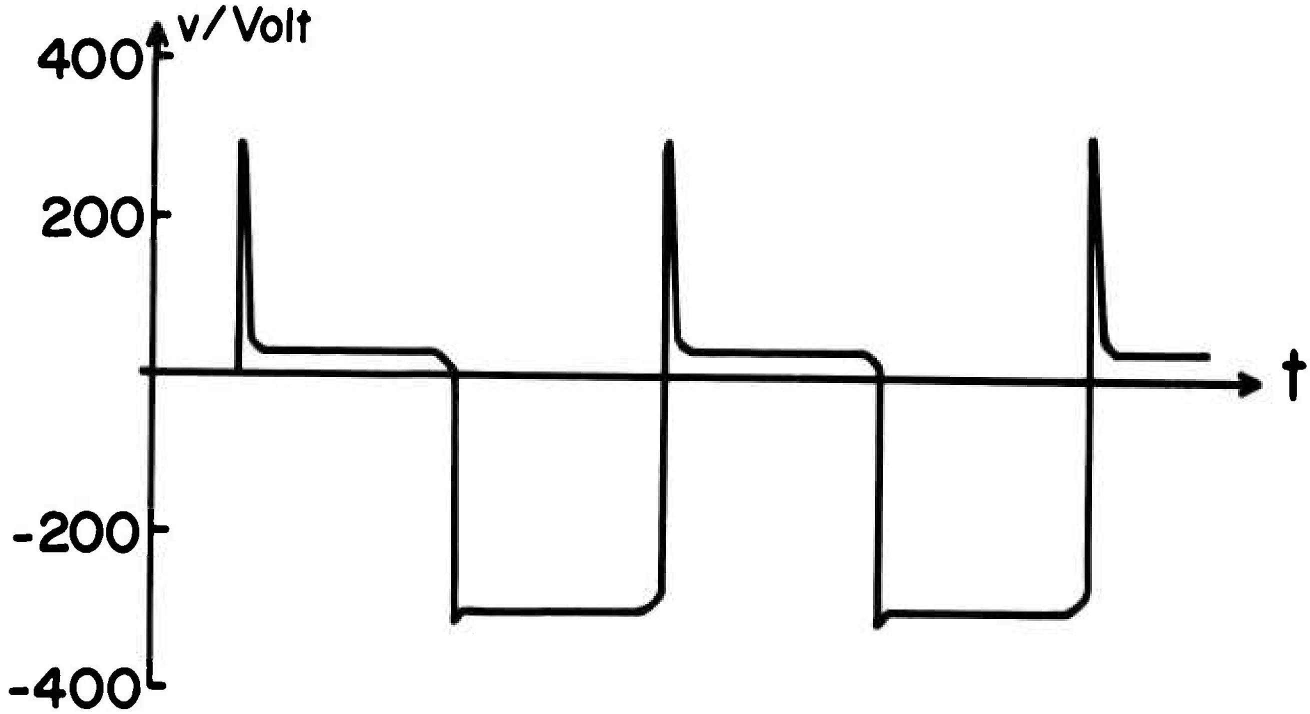


Figure 11

Voltage waveform of asymmetrical discharge with very large value of R_s.

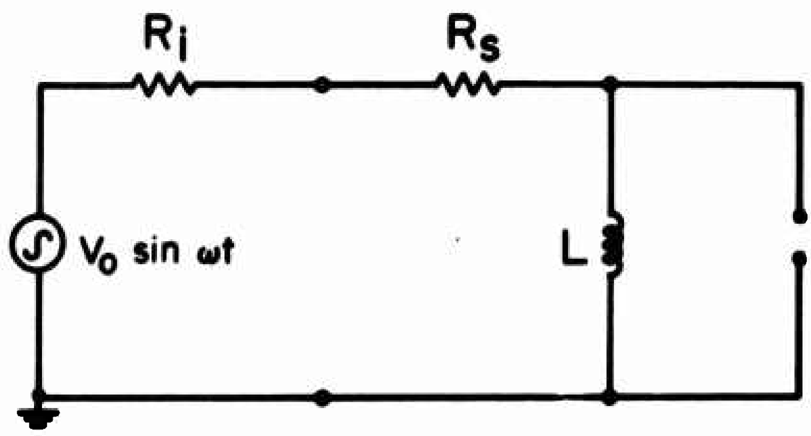


Figure 12

Circuit for discharges with zero dc component of discharge voltage

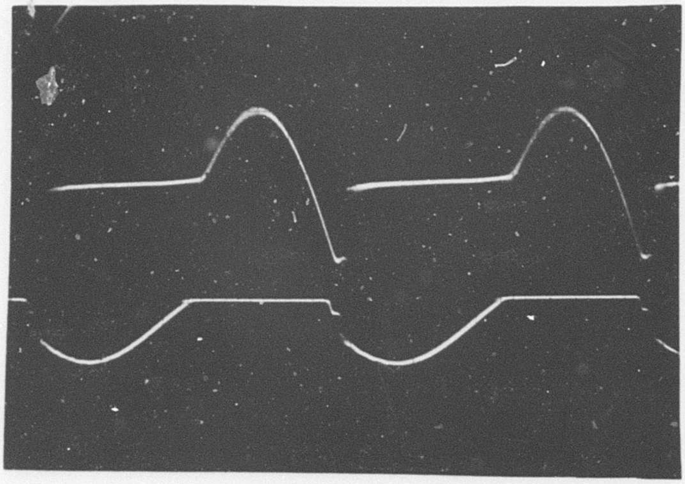


Figure 13

Voltage and current waveforms of asymmetrical discharge obtained with circuit of Figure 12. $R_s = 500\Omega$; $d = 0.25$ mm; $f = 1$ MHz
Upper trace: Voltage, 250 V/div; lower trace: current, 2 A/div.

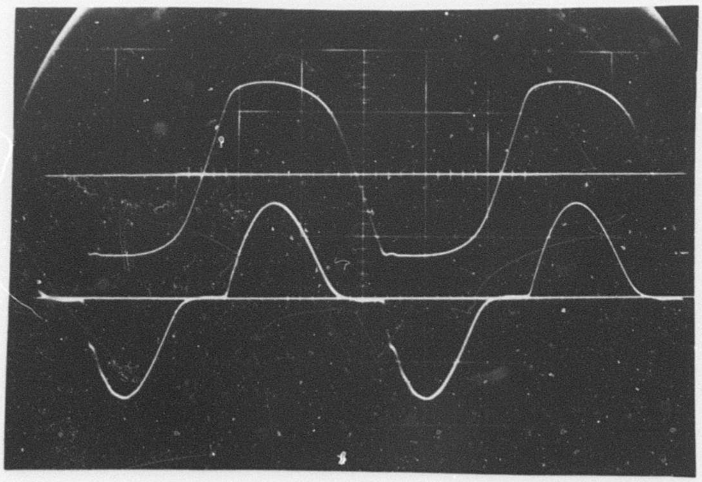
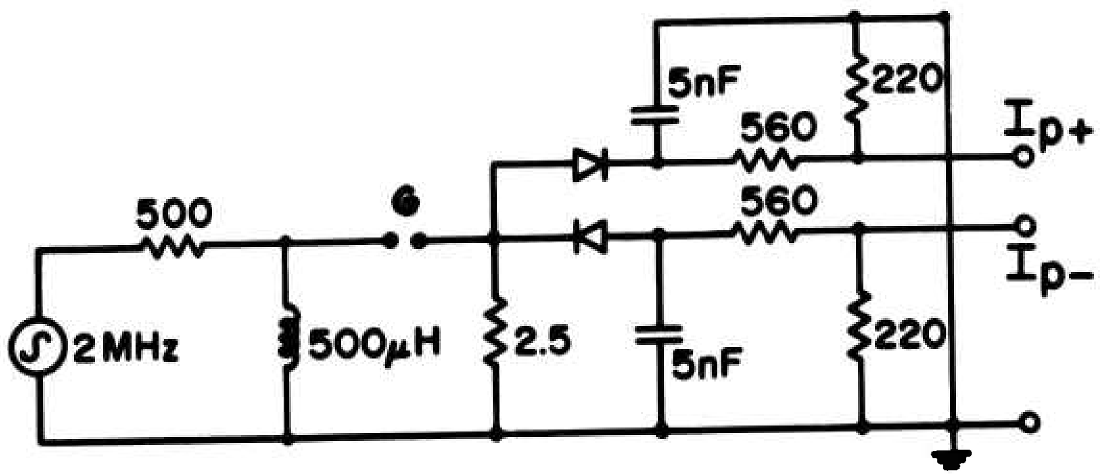


Figure 14

Waveforms of asymmetric glow discharge. $R_s = 500\Omega$; $d = 0.25$ mm; $f = 1$ MHz.
Upper trace: voltage, 250 V/div; lower trace: current 0.4 A/div.



All resistance values in Ω.

Figure 15

Circuit used to study low frequency components produced by asymmetrical discharges.

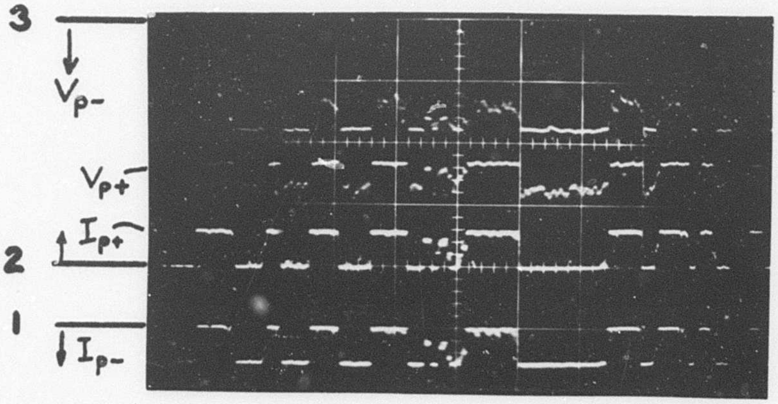
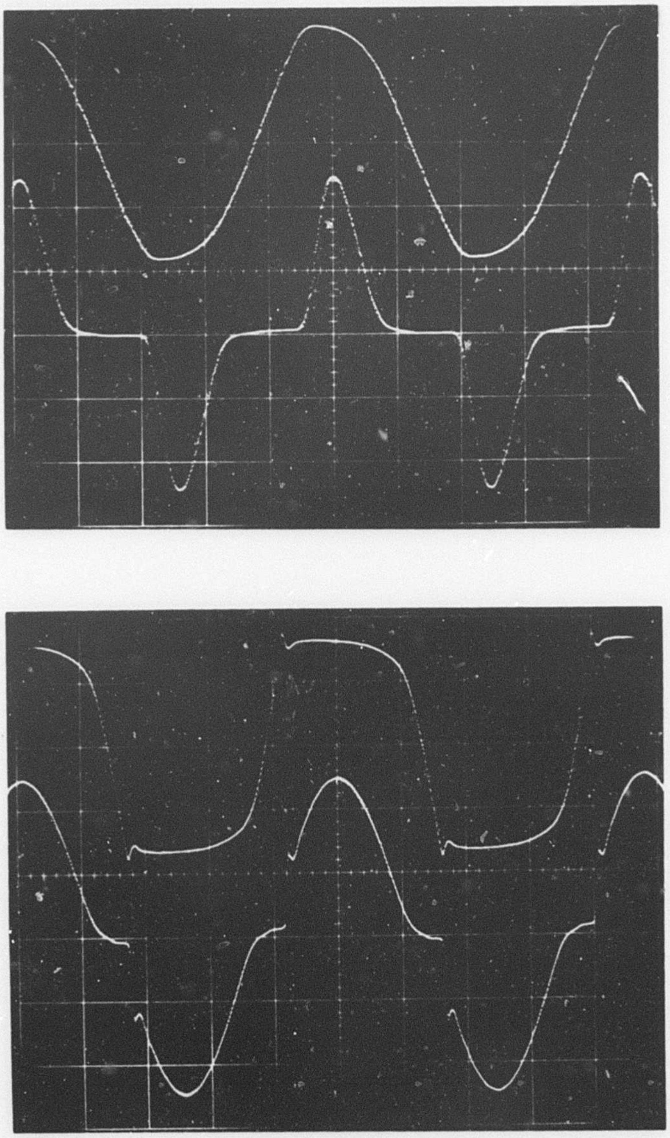


Figure 16

Low frequency components produced by discharge. Traces from top to bottom: V_{p-}, V_p+, I_{p+}, I_{p-}. Amplitude scale is relative; time: 1 ms per major division.



a)

b)

Figure 17

Glow discharge waveforms with a) R_s = 100Ω; b) R_s = 2000Ω; d = 0.125 mm; f = 1 MHz.
Upper traces: voltage, 200 V/div; lower traces: current, 0.2 A/div.

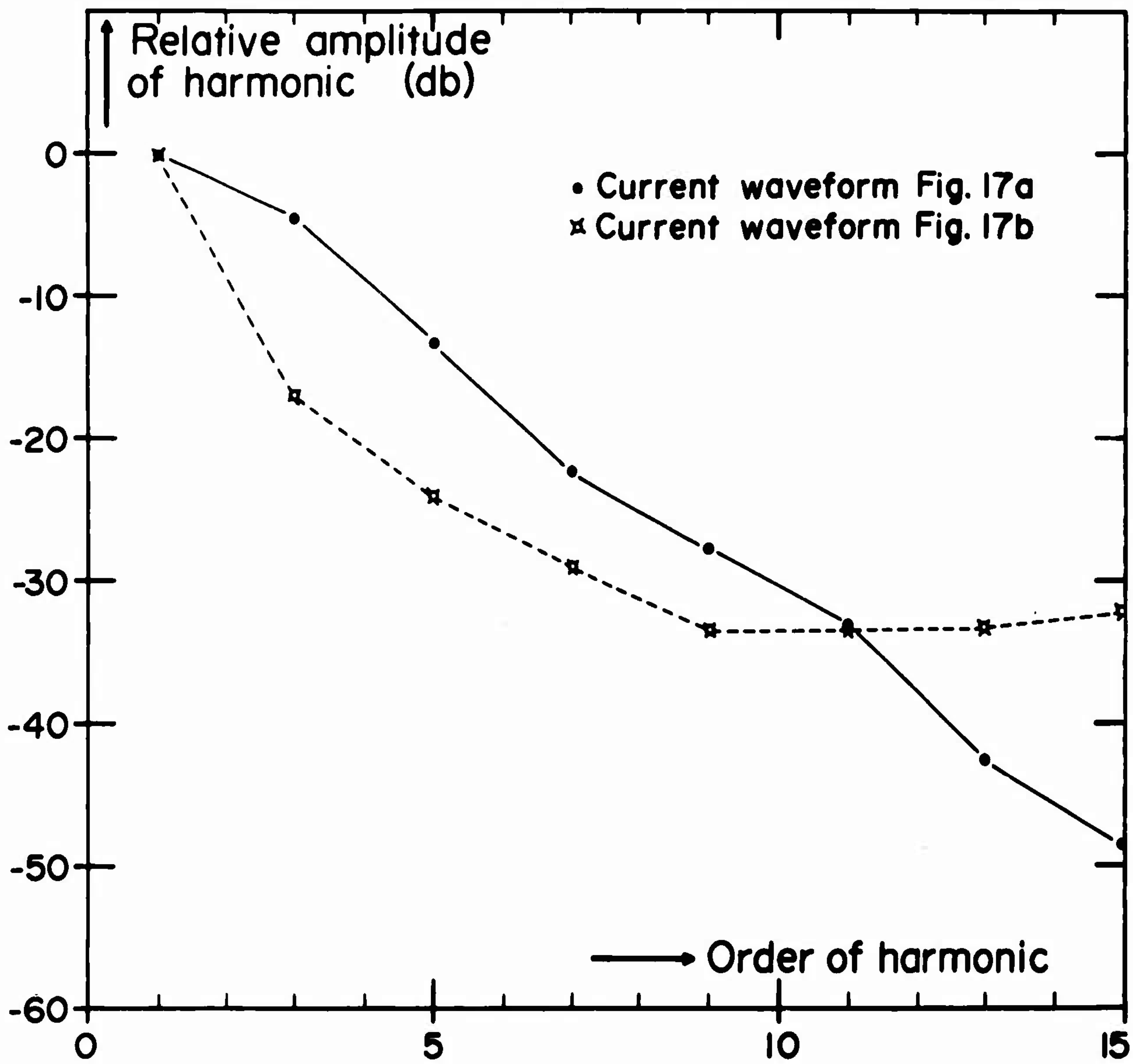


Figure 1[illegible]

Amplitude spectra of current waveforms of Figure 17.

REFERENCES

(1) W. E. Pakala, E. R. Taylor, and R. T. Harrold, "Radio Noise Measurements on High Voltage Lines from 2.4 to 345 kV", *1968 IEEE Electromagnetic Compatibility Symp. Rec.*, p. 96.

(2) J. Davey, H. L. Deloney and J. J. LaForest, "Effect of Station Radio Noise Sources on Transmission Line Noise Levels–Experimental Results", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-86, No. 8, August 1967, p. 1007.

(3) H. A. Schwab, "Electrical Properties of RF Glow Discharges in Air at Atmospheric Pressure", U. S. Naval Weapons Laboratory, Dahlgren, Va., Report No. 2124, Nov. 1967.

(4) R. Henkel and D. Mealey, "Electromagnetic Compatibility Operational Problems Aboard the Apollo Spacecraft Tracking Ship". *1967 IEEE Electromagnetic Compatibility Symp. Rec.*, p. 70.

(5) R. F. Elsner, et al. "Environmental Interference Study Aboard a Naval Vessel", *1968 IEEE Electromagnetic Compatibility Symp. Rec.*, p. 330.

(6) H. A. Schwab and C. K. Manka, "A Study of Charge Transport in a High-Pressure rf Discharge", *J. Appl. Phys.*, Vol. 40, No. 2, p. 696, Feb. 69.

(7) H. A. Schwab and R. F. Hotz, "Reignition Voltage in a High-Pressure rf Discharge", *J. Appl. Phys.*, Vol. 41, No. 4, March 1970.

(8) W. A. Gambling and H. Edels, "The High-Pressure Glow Discharge in Air", *Brit. Journ. Appl. Phys.*, 5, 36 (1954).

(9) G. Francis, "The Glow Discharge at Low Pressure", *Encyclopedia of Physics*, S. Fluegge, Ed., (Springer-Verlag, Berlin, 1956) Vol. XXII, p. 53.

(10) A. v. Engel, *Ionized Gases* (Clarendon Press, Oxford, England, 1965), p. 217.

(11) R. C. Fletcher, "Impulse Breakdown in the 10^{-9} Sec. Range of Air at Atmospheric Pressure", *Phys. Rev.*, Vol. 76, No. 10, Nov. 1949, p. 1501.

UNCLASSIFIED

Security Classification

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY (Corporate author)
U. S. Naval Weapons Laboratory
Dahlgren, Virginia

2a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

2b. GROUP

3. REPORT TITLE
PARASITIC RF GAS DISCHARGES AS RECTIFIERS AND INTERFERENCE GENERATORS

4. DESCRIPTIVE NOTES (Type of report and inclusive dates)

5. AUTHOR(S) (First name, middle initial, last name)
HELMUT A. SCHWAB

6. REPORT DATE
August 1970

7a. TOTAL NO. OF PAGES

7b. NO. OF REFS

8a. CONTRACT OR GRANT NO.

b. PROJECT NO.

c.

d.

9a. ORIGINATOR'S REPORT NUMBER(S)
TR-2470

9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report)

10. DISTRIBUTION STATEMENT
Distribution of this document is unlimited. (CNM Control No. 1134)

11. SUPPLEMENTARY NOTES

12. SPONSORING MILITARY ACTIVITY

13. ABSTRACT

Gas discharges can be maintained in air at atmospheric pressure by rf power. In high intensity fields, for example in the vicinity of radiating antennas, enough power can be coupled into conducting structures to make parasitic discharges possible. They may be started when intermittent contact between conductors is made. It has been found that the discharges are of two distinct types, an rf glow and an rf arc type. If the discharge type alternates with the polarity, highly asymmetric voltage current characteristic result. This allows rf discharges to rectify rf currents. By their nonlinear characteristics they also produce numerous harmonics of the frequency at which they are maintained. Thus parasitic rf discharges can act as broad band interference generators.

DD FORM 1 NOV 65 1473 (PAGE 1)

S/N 0101-807-6811

UNCLASSIFIED

Security Classification

A-31408